Did Something Decay, Evaporate, or Annihilate during Big Bang Nucleosynthesis?

Karsten Jedamzik

Laboratoire de Physique Mathémathique et Théorique, C.N.R.S.,
Université de Montpellier II, 34095 Montpellier Cedex 5, France

Results of a detailed examination of the cascade nucleosynthesis resulting from the putative hadronic decay, evaporation, or annihilation of a primordial relic during the Big Bang nucleosynthesis (BBN) era are presented. It is found that injection of energetic nucleons around cosmic time 10^3sec may lead to an observationally favored reduction of the primordial ^{7}Li/H yield by a factor $2-3$. Moreover, such sources also generically predict the production of the ^{6}Li isotope with magnitude close to the as yet unexplained high ^{6}Li abundances in low-metallicity stars. The simplest of these models operate at fractional contribution to the baryon density $\Omega_b h^2 \gtrsim 0.025$, slightly larger than that inferred from standard BBN. Though further study is required, such sources, as for example due to the decay of the next-to-lightest supersymmetric particle into GeV gravitinos or the decay of an unstable gravitino in the TeV range of abundance $\Omega_{\tilde{G}} h^2 \sim 5 \times 10^{-4}$ show promise to explain both the ^{6}Li and ^{7}Li abundances in low metallicity stars.

Big Bang nucleosynthesis has since long been known as one of the most precise and furthest back-reaching probes of cosmic conditions and the cosmic matter content of the early Universe. It thus, for example, has significantly contributed to the notion that a large fraction of matter in present-day galaxies is believed to be of non-baryonic nature as well as considerably limited some extensions of the standard model of particle physics. Paramount to having become such a useful tool of cosmology was and is, not only the examination of early synthesis of light elements in it's simplest standard version, but also in a variety of non-standard, alternative scenarios, relaxing a priori non-verified assumptions entering the calculations of a standard BBN (SBBN). Depending on the light element yields obtained in these latter scenarios, such calculations may then either favor a modified version of BBN, or strengthen the case for the SBBN. In either case, calculations of non-standard BBN may be used to place limits on the cosmic condition in the early Universe. In this spirit, technically advanced calculations of BBN including decaying particles during, or after BBN, an inhomogeneous baryon distribution, small-scale antimatter domains, neutrino degeneracy, or varying fundamental constants (for reviews cf. [1]), among others, have been performed over the years, rendering SBBN (also by the principle of Occam's razor) as our preferred scenario for BBN

On the observational side significant advances have been made with the advent of high-resolution spectrographs on the Keck- and VLT-telescopes and the resulting capability to perform D/H abundance determinations of unprecedented accuracy in a few simple high-redshift quasar absorption line (QAL) systems. Furthermore an independent determination of the fractional contribution of baryons to the critical density, Ω_b, from precision measurements of the cosmic microwave background radiation (CMB) by various balloon missions and the WMAP [2] sattelite has become feasible. These observations together with the ever-continuing observational and theoretical efforts to deduce precise primordial ^{4}He/H- and ^{7}Li/H- ratios, leave BBN in an essentially observationally overconstrained state, opening the possibility to question internal consistency of the predictions of SBBN. If such a check is performed it shows that SBBN is to first approximation internally consistent, though inconsistencies or tensions between predicted- and observationally inferred-abundances may exist at higher order. It is the subject of this paper to propose a scenario of non-standard BBN which may remove some of these tensions.

If the central value of the observationally determined D/H$= 2.78^{+0.44}_{-0.38} \times 10^{-5}$ [3, 4] by the average of five QAL systems is taken, SBBN predicts ^{7}Li/H$\approx 4.16 \times 10^{-10}$, a ^{4}He mass fraction $Y_p \approx 0.2480$ at an $\Omega_b h^2 \approx 0.0218$. I refrain from the common practice to give error bars due to nuclear reaction rate uncertainties on the theoretical predictions, as there exist surprisingly large differences between the central values obtained by different groups, often larger than the quoted error bars, particularly in the case of ^{7}Li [5]. The predicted ^{7}Li should be compared to the observationally inferred primordial ^{7}Li/H$= 1.23^{+0.34}_{-0.16} \times 10^{-10}$ [10] abundance from the inferred ^{7}Li in atmospheres of extreme Pop II stars belonging to the Spite plateau (where the analysis corrects for ^{7}Li production by cosmic rays), or to the inferred ^{7}Li $= 2.19^{+0.30}_{-0.27} \times 10^{-10}$ [11] from low-metallicity stars within the globular cluster NGC 6397, indicating if taken at face value, that there may be a problem in SBBN. This discrepancy may not be resolved by nuclear reaction rate uncertainties in the main lithium-producing reaction ^{3}He$(\alpha, \gamma)^7$Be [7] and only very unlikely due to uncertainties in the lithium-destroying reaction ^{7}Be$(d, p)2^4$He [8]. It is conceivable, however, that it is due to other systematic uncertainties entering the inference of primordial ^{7}Li abundances, such as stellar astration of ^{7}Li in low-metallicity stars, or imprecise determinations of stellar surface temperatures in these stars. Recent 3D non-LTE (i.e. local-thermodynamic-equilibrium) calculations [12] of lithium lines in low-metallicity stars indicate, however, that simplifying assumptions concerning the stellar atmosphere probably do not introduce excessively large systematic errors.

Stellar ^{7}Li may be destroyed by ^{7}Li$(p,\alpha)^4$He when transported deep enough into the interior of the star, as for example due to stellar rotation induced turbulence or diffusion. The mixing possibilities proposed are numerous, however, many fail on the requirement to deplete ^{7}Li in different stars of different surface temperatures and rotation velocities by a substantial factor ($\sim 2 - 4 \equiv 0.3 - 0.6$ dex) neither introducing scatter in the observationally inferred ^{7}Li/H nor a trend of depletion with surface temperature. Moreover, ^{7}Li has to be depleted without substantial depletion of the more fragile ^{6}Li [13, 14] isotope observed in at least two of these stars along with that of ^{7}Li. The large abundance of the ^{6}Li isotope at such low metallicity is anyway theoretically challenging, even in the absence of stellar depletion (see below). Recent detailed stellar studies [15, 16] and an analysis [17] of the samples of ^{7}Li/H abundances employed to infer the primordial ^{7}Li/H ratio claim that, under certain conditions, a uniform depletion of 0.2-0.3 dex may be possible, though there remains lack of observational indication for this, in fact, to be the case [11].

Concerning the abundance of ^{4}He there exists as well a mismatch between the relatively high prediction and the lower observationally inferred value $Y_p = 0.02390 \pm 0.0020$ [18] (with another group finding $Y_p = 0.2421 \pm 0.0021$ [19]). I will not much further elaborate on this discrepancy here, since the abundance of ^{4}He, whose observational determination is plagued by various systematic uncertainties, will hardly change in the scenarios I consider. Last but not least, there is the vital comparison between the $\Omega_b h^2$ as inferred from the CMB and $\Omega_b h^2$ as preferred by SBBN and D/H. The inferred baryon density when the WMAP data only is taken [2] (with a power-law ΛCDM model) is $\Omega_b h^2 = 0.024 \pm 0.001$, whereas a running spectral index ΛCDM model results in a value lower by 0.001. When data from other experiments, of CMB and/or large-scale structure, probing smaller scales than WMAP are included, the estimated $\Omega_b h^2$ drops to around 0.0225 (for combined likelihoods between $\Omega_b h^2$ estimates from CMB and SBBN cf. to Ref. [9]). In general the agreement between CMB and SBBN (plus D/H) is excellent, with nevertheless CMB inferred $\Omega_b h^2$ values typically staying on the high side of those preferred by SBBN. Thus non-standard BBN scenarios are not allowed to operate with $\Omega_b h^2$ much different than those of SBBN.

At such large $\Omega_b h^2$ the bulk of ^{7}Li is produced as ^{7}Be (which is after BBN converted to ^{7}Li). It is a not widely recognized effect that ^{7}Be may be prematurely destroyed via the reaction chain ^{7}Be$(n,p)^7$Li and ^{7}Li$(p,\alpha)^4$He by significant factors when towards the end of BBN, at approximate temperatures $30 - 50$ keV a small excess of free neutrons n/p $\sim 10^{-5}$ as compared to SBBN exists. This phenomena has been observed in both studies of inhomogeneous BBN [20] as well as studies with hadronically decaying particles [21]. Such an excess could thus possibly result from the hadronic decay or evaporation of a relic of the early Universe. Thermal neutrons injected at these temperatures are predominantly incorporated into
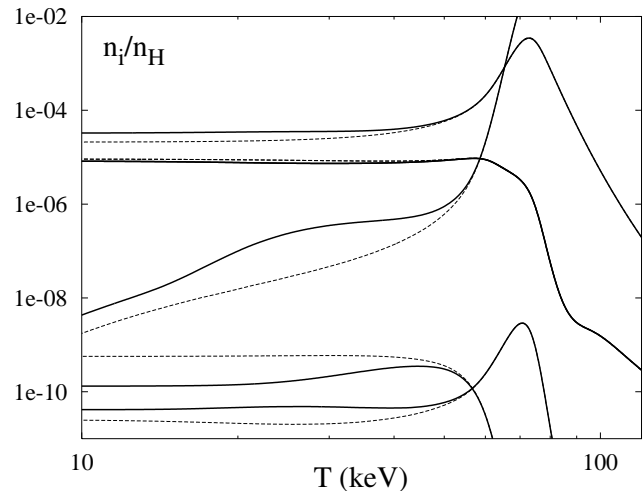

FIG. 1: Light element evolution as function of temperature with (solid) and without (dashed) a thermal neutron source. Shown are, from top to bottom (at lower temperatures), the number ratios n_D/n_p, $n_{^3\mathrm{He}}/n_p$, n_n/n_p, $n_{^7\mathrm{Be}}/n_p$, and $n_{^7\mathrm{Li}}/n_p$, respectively. See text for further detail.

D via p(n,γ)D, with a small fraction $\sim 10^{-4} - 10^{-5}$ causing the premature conversion of ^{7}Be to ^{7}Li. It is straightforward to show that to convert one ^{7}Be nucleus $\langle\sigma v\rangle_{\mathrm{p\,n}}/\langle\sigma v\rangle_{^7\mathrm{Be\,n}} \times \mathrm{H}/^7$Be neutrons are required. Due to the ^{7}Be$(n,p)^7$Li reaction being between mirror nuclei, the rate ratio in the above is very small $\approx 1.4 \times 10^{-5}$. This implies that the conversion of essentially all ^{7}Be to ^{7}Li is accompanied by only a mild (^{7}Be/H -independent) excess of D/H $\approx 1.4 \times 10^{-5}$, when compared to SBBN. Of course, not all of the thus produced ^{7}Li will subsequently be destroyed via ^{7}Li$(p,\alpha)^4$He, in particular at low temperatures where the Coulomb barrier is preventing the reaction. Neutrons which are injected at slightly higher temperatures are further processed into ^{4}He. Nevertheless, this possible excess in ^{4}He is essentially negligible due to the small numbers of neutrons required to destroy ^{7}Be.

I have slightly modified the Kawano code in order to test for this effect. In particular, I have injected thermal neutrons with rate $dn_n/dt \sim \exp(-t/\tau)/\tau$ and decay time $\tau = 700$ s employing a total injected neutron abundance corresponding to $\Omega_n h^2 \approx 10^{-6}$. In Fig. 1 the light-element synthesis in the presence (and absence) of such a neutron source is shown, assuming $\Omega_b h^2 = 0.026$. It is seen that the neutrons in fact yield the desired destruction of ^{7}Be and some comparatively smaller enhancement in ^{7}Li. The yields for D/H and ^{7}Li/H, with (and without) extra neutrons are 3.25×10^{-5}, (2.09×10^{-5}), and 1.73×10^{-10}, (5.92×10^{-10}), respectively, resulting in a 0.53 dex "depletion" of the ^{7}Li yield. The ^{4}He abundance remains virtually unchanged (except for an increase by $\Delta Y_p \approx 0.002$ on account of the increased $\Omega_b h^2$ with respect to the above quoted value).

The effect is encouraging and may present a possible

resolution to the ^{7}Li problem in SBBN. Nevertheless, many viable hadronically decaying, evaporating, or annihilating candidates inject energetic hadrons rather than thermal neutrons. A massive $m_{\tilde{G}} \sim 200$ GeV decaying particle, for example, would lead to the injection of protons and neutrons with typical energies ~ 8 GeV reaching up to several tens of GeVs. These are accompanied, of course, by much larger numbers of pions, $e^\pm$, neutrinos, and photons. Cascade nucleosynthesis due to energetic electromagnetically interacting particles may not be of immediate interest here, not only because it is operative at lower $T \lesssim 3$ keV, but also since the small required neutron densities to resolve the ^{7}Li discrepancy may not imply much of an effect. Similarly, n↔p interconversion by mesons [21, 22], potentially important at higher temperatures, has a negligible effect due to the smallness of the assumed perturbation. I caution though that these conclusions are dependent on the injected meson- and baryon- multiplicities, and the ratio of electromagnetically to hadronically interacting particles, and are strictly only valid in the context of strongly interacting jet dynamics. In contrast, spallation of ^{4}He by energetic nucleons is important, and has heretofore only been considered after BBN by the pioneering study of Ref. [23] (cf. also to [24]), and with an amount of injected nucleons far larger than of interest here. Similar holds for nonthermal nucleosynthesis, in particular, the reactions ^{3}H$(\alpha,n)^6$Li and ^{3}He$(\alpha,p)^6$Li with energy threshold induced by energetic ^{3}H and ^{3}He (themselves produced by the spallation of ^{4}He) are of paramount importance for the ^{6}Li abundance.

The large abundance of ^{6}Li in low-metallicity Pop II stars is a bit of a mystery. It has been observed in at least three stars at low metallicity [Fe/H]< -2 with the best case probably the star HD84937 with ^{6}Li/^{7}Li$= 0.052 \pm 0.019$ [25], as well as in two stars at higher metallicity [Fe/H]≈ -0.6 [26], with all abundance ratios coincidentally being similar [27]. ^{6}Li is traditionally not thought to be of primordial origin due to the cross section D$(\alpha,\gamma)^6$Li, absent of threshold, being small [28]. ^{6}Li is thus believed to have its origin in cosmic-ray nucleosynthesis, being produced along-side with ^{7}Li (to be added to the BBN yield), ^{9}Be, ^{10}B, and ^{11}B via spallation (p, $\alpha+$CNO $\rightarrow$ LiBeB) and fusion ($\alpha+\alpha \rightarrow$ Li) reactions by galactic cosmic rays. It is rather controversial as to whether [29], or not [30, 31], it is possible to produce the large observed ^{6}Li abundance in Pop II stars via cosmic rays generated by thermonuclear or core-collapse supernovae, even when so far unknown cosmic ray populations (e.g., low-energy and metallicity-dependent) are postulated. The problem, in general, seems to be that in order to reproduce the approximate linear relationship between ^{9}Be/H and [Fe] metal-enriched cosmic rays are strongly favored. Such metal-enriched cosmic rays yield typical spallation ^{6}Li/^{9}Be-ratios $\sim 5-20$ agreeing with the ratio ≈ 6 in the solar system, but not with the ratio ~ 80 as observed in Pop II stars. It may be that there exists an enhanced fusion contribution (with cosmic rays at $\sim$ 30 MeV/nucleon) at high redshifts, and though it may be energetically problematic when associated with stellar evolution [30], it could be due to virialization shocks during structure formation [32]. Nevertheless, the origin of ^{6}Li in Pop II stars seems currently controversial. This situation has led me to consider alternative production of ^{6}Li due to non-thermal nucleosynthesis after BBN [33, 34], resulting from electromagnetic cascade nucleosynthesis.

Production of ^{6}Li due to nuclear spallation and fusion reactions towards the end of BBN may as well be very efficient. I have performed a detailed Monte-Carlo analysis of the cascade nucleosynthesis resulting from the decay, evaporation, or annihilation of strongly interacting particles or defects. To reach a precision to allow for a meaningful comparison to the comparatively accurate observational determinations of D/H, ^{6}Li/H, ^{7}Li/H, and $\Omega_b h^2$, care had to be taken. The analysis includes a detailed modeling of elastic nucleon-nucleon and nucleon-^{4}He scattering. It includes also their important inelastic ($pp, np \rightarrow pp, pn, nn + \pi's$ and p, n^4He $\rightarrow \, ^3$He, ^{3}H, D$'s + n's, p's + \pi's$) counterparts employing detailed cross section data. A careful treatment of the recoil energies of ^{4}He (from elastic scattering), as well as ^{3}H and ^{3}He (from ^{4}He spallation) has been incorporated. These recoil energy distribution functions are important for a determination of ^{6}Li yields resulting from the reactions ^{3}H$(\alpha,n)^6$Li, ^{3}He$(\alpha,p)^6$Li, ^{4}He$(\alpha,2p)^6$He, ^{4}He$(\alpha,pn)^6$Li. Finally, as thermalization of nucleons, and nuclei, is a competition between nuclear scattering and Coulomb interactions with the plasma, in the case of protons and nuclei, and nuclear scattering and magnetic moment scattering on $e^\pm$, in the case of neutrons, these latter interactions also had to be included [35]. A detailed account of the analysis, which is beyond the scope of the present paper, will be presented elsewhere. These processes have been coupled to the Kawano code [36] (updated by the NACRE [37] reaction compilation). Finally, the primary spectrum of injected nucleons is computed with the help of the jet fragmentation code PYTHIA [38]

The development of a nuclear cascade may be summarized as follows. For temperatures above $T \gtrsim 20$ keV protons are essentially exclusively thermalized by electromagnetic interactions with the still abundant $e^\pm$ pairs. At lower temperatures, thermalization for energetic protons (and nuclei) $E_{\rm kin} \gtrsim 1$ GeV occurs via scattering on plasma protons and ^{4}He, as well as Thomson scattering on CMBR photons, while less energetic protons loose energy via Coulomb scattering and plasmon excitation. In contrast, neutrons thermalize on plasma protons and ^{4}He up to temperatures of $T \approx 50-60$ keV. For higher T the dominant energy loss is due to $ne^\pm$-scattering, with the most rapid fractional energy loss for energetic neutrons ($\gamma \gg 1$). Thermalization of nucleons and nuclei occurs rapidly when compared to the cosmic expansion rate. Interactions of rapid nucleons on protons (and ^{4}He) at $E_{\rm kin} \gtrsim 1$ GeV are to a large fraction (~ 0.75) inelastic, accompanied by the production of pions. During such

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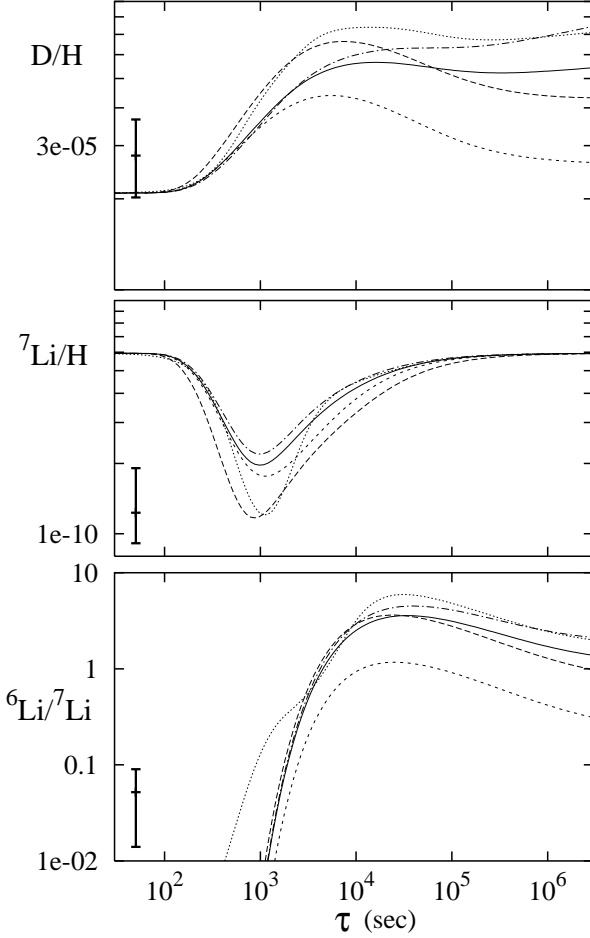FIG. 2: Abundance yields of D/H, ^{7}Li/H, and ^{7}Li/^{6}Li in an $\Omega_b h^2 = 0.026$ Universe as function of the hadronic decay time τ of a putative primordial relic. The models are decay of a $m_\chi = 10$ GeV particle (long-dashed), decay of a $m_\chi = 200$ GeV particle (solid), decay of a $m_\chi = 4$ TeV particle (dashed-dotted), injection of monoenergetic nucleons of $E_{kin} = 250$ MeV (short-dashed), and extended power-law injection due to a $m_\chi = 200$ GeV particle (dotted). Also shown are the two-sigma ranges of the inferred primordial D/H and ^{7}Li/H abundances [3, 10] as well as the ^{6}Li/^{7}Li ratio as inferred in the low-metallicity star HD84937 [25]. See text for further details.

scatterings an interconversion of protons to neutrons occurs frequently, such that energetic protons produce secondary neutrons. For example, though the decay of a 200 GeV particle generates only about ≈ 1 neutron per annihilation, around $\approx 1, 0.6$ secondary neutrons result at $T \approx 20, 40$ keV, respectively [39], and ≈ 3.5 asymptotically at low temperatures $T \sim 0.1-1$ keV. Here at higher temperatures the number of secondary neutrons reduces due to the rapid Coulomb losses of protons. Neutrons, on the other hand, do not possess a significant bias towards producing secondary neutrons in np inelastic inter-

actions. Excess neutrons at $T \approx 40$ keV are mostly due to inelastic processes on ^{4}He, accompanied by the production of D and ^{3}He (i.e. $n+^4$He $\to$ D+p+2n, ...), with a comparatively smaller amount of neutrons removed in pionic fusion processes (i.e. $np \to$ Dπ^0, ...). One thus obtains approximately a ratio n/D ≈ 3.6 for a 200 GeV particle at $T \approx 40$ keV, with similar ratios for n/^{3}H and n/^{3}He. As the ^{3}H and ^{3}He are energetic they may yield the production of ^{6}Li. Nevertheless, ^{6}Li production (and survival) may only be efficient at somewhat lower temperatures. Due to Coulomb losses of energetic ^{3}H and ^{3}He production is only efficient at $T \lesssim 20$ keV, whereas survival of the freshly synthesized ^{6}Li against destruction via ^{6}Li$(p,\alpha)^3$He is only nearly complete for $T \lesssim 10$ keV. The production of ^{6}Li at temperatures $T \approx 10-20$ keV for a 200 GeV particle is found to be approximately 2×10^{-4} per decaying particle, becoming significantly lower at lower temperatures (e.g. 3×10^{-5} at $T \approx 1$ keV). Cascade yields are subject to some nuclear physics data uncertainties which in the case of ^{6}Li may be of the order of a factor two. In particular, it may be that ^{6}Li yields are underestimated due to an experimentally incomplete determination of the high-energy tail of the energy distribution of energetic ^{3}H and ^{3}He produced in ^{4}He spallation.

The developed code allows me to present detailed predictions on the BBN in the presence of decaying particles. Figure 2 shows the light-element yields for a variety of decaying particles as a function of particle life time τ. The panels show, from top-to-bottom, final abundances of D/H, ^{7}Li/H, and ^{6}Li/^{7}Li, with the understanding that Y_p is virtually unchanged when compared to SBBN at the same $\Omega_b h^2$. In all models $\Omega_b h^2 = 0.026$ has been assumed. Hadronically decaying particle yields (with the simplifying assumption that $\chi \to q\bar{q}$ yields the production of a pair of quarks, the up-quark for definiteness) are shown for three particle masses: $m_\chi = 10$ GeV with $\Omega_\chi h^2 = 7.5 \times 10^{-5}$ (long-dashed), $m_\chi = 200$ GeV with $\Omega_\chi h^2 = 1 \times 10^{-4}$ (solid), and $m_\chi = 4$ TeV [40] with $\Omega_\chi h^2 = 6 \times 10^{-4}$ (dashed-dotted). It is evident that for decay times around $\tau \approx 10^3$s an efficient destruction of ^{7}Li is obtained. For τ much shorter than 10^3s the destroyed ^{7}Be is regenerated, whereas for τ much longer, incomplete ^{7}Li burning in the reaction chain ^{7}Be$(n,p)^7$Li$(p,\alpha)^4$He results in only partial reduction of the total ^{7}Li yield. As anticipated, the destruction of ^{7}Li is accompanied by production of D. When compared to the injection of thermal neutrons, D/H yields are higher. This is due to D generated in the nuclear cascade itself (i.e. by ^{4}He spallation and pionic fusion). Cascade generated deuterium (as well as ^{3}H, ^{3}He, and ^{6}Li) is substantially reduced per injected neutron for sources which inject nucleons with a soft spectrum. For example, I have also employed a soft source with monoenergetic nucleons of 250 MeV. Results for this case are shown by the short-dashed line, assuming $\Omega_\chi h^2/m_\chi \approx 7.5\times10^{-7}$GeV^{-1} and the injection of one np pair per decay [41]. A cascade n/D ≈ 10 ratio at $T \approx 40$ keV is obtained in such scenarios. The more pronounced depth of the ^{7}Li dip in Fig.

2, by comparable (or smaller) D production, indicates that soft sources may affect a larger destruction factor in ^{7}Li while respecting an appropriate upper limit on the primordial D/H-ratio.

Concerning production of ^{6}Li it is observed that yields of the order of ^{6}Li/^{7}Li $\approx 5 \times 10^{-2}$, as observed in extreme low-metallicity Pop II stars, are obtained for decay times in the range $\tau \approx 1 - 2 \times 10^3$s. For such τ, substantial ^{7}Li destruction is also observed, since minimal ^{7}Li production usually occurs for τ between 800 and 10^3s. The slight mismatch between the "perfect" decay time for ^{7}Li destruction when compared to that for ^{6}Li production is related to the more efficient destruction of ^{6}Li (via ^{6}Li$(p, \alpha)^3$He) as compared to the analogous reaction for ^{7}Li. It also depends on the total ^{6}Li yield per decaying particle and may disappear if their exists a factor two underestimate in this quantity. However, it is not necessary that both decay times are equal, as even when not, observationally acceptable scenarios may result. This is illustrated in Table 1, which shows the abundance yields of a few selected models, generally in good agreement with the observational value of all three isotopes D, ^{7}Li, and ^{6}Li. If it all than the abundance of D $\sim 4 \times 10^{-5}$ in these decaying particle scenarios is somewhat large.

It is tempting to adjust for this slight mismatch by resorting to somewhat less in the literature discussed possibilities of hadronic energy injection than that of a massive decaying particle (such as the gravitino). These may include unstable Q-balls [42] or semistable strange-quark matter nuggets formed during a QCD-transition [43], among others. What is desired is a prolongation of the injection, as compared to the decay of a particle. This may be, for example, due to a population of Q-balls of varying sizes. As a detailed analysis is beyond the scope of this exploratory paper, I simply model the temporal injection of such a putative source by $dn_Q/dt = n_Q^0/\tau \min[(t/\tau)^{-3}, 1]$, including a long time injection tail. Here the spectrum of the primary and secondary cascade products is taken to be that of a $200\,$GeV $q\bar{q}$ event and $\Omega_Q h^2 = 10^{-4}$ has been assumed. Results for this case are given by the dotted line in Fig.2, and for one particular τ on the last row of Table 1. It is seen, that for such "extended" emission all, the D/H, ^{7}Li/H, and ^{6}Li/^{7}Li abundance constraints may be well satisfied. As another possibility I mention sources which have an unusually large ratio between electromagnetic and hadronic energy injection ($\sim 10^2 - 10^3$). If emission lasts to around times of 10^5s, a substantial fraction of D (as well as ^{6}Li) may be photodisintegrated. Nevertheless, such sources have subsequently to stop radiating fairly abruptly, as otherwise an overproduction of ^{6}Li (either via ^{7}Li photodisintegration or electromagnetic cascade nucleosynthesis [33]) results. Note, that this is also the reason that the recently proposed ^{7}Li photodisintegration as a solution to the comparatively high predicted ^{7}Li abundance may not apply [44].

Extended emission during BBN may result as well from annihilating particles. Since a supersymmetric neu-

TABLE I: Light-element abundances for a few selected decaying particle and extended emission scenarios. All models assumme $\Omega_b h^2 = 0.026$. See text for further details.

model	τ(s)	D/H	^{7}Li/H	^{6}Li/^{7}Li
thermal neutrons	$7 \cdot 10^2$	$3.3 \cdot 10^{-5}$	$1.7 \cdot 10^{-10}$	$\lesssim 10^{-3}$
soft source	$1.8 \cdot 10^3$	$4.0 \cdot 10^{-5}$	$1.9 \cdot 10^{-10}$	0.03
decay $m_\chi = 10$ GeV	$1.5 \cdot 10^3$	$5.1 \cdot 10^{-5}$	$1.4 \cdot 10^{-10}$	0.04
decay $m_\chi = 200$ GeV	$1.5 \cdot 10^3$	$4.1 \cdot 10^{-5}$	$2.1 \cdot 10^{-10}$	0.03
decay $m_\chi = 4$ TeV	$1.5 \cdot 10^3$	$4.0 \cdot 10^{-5}$	$2.4 \cdot 10^{-10}$	0.03
extended emission	$7.1 \cdot 10^2$	$3.6 \cdot 10^{-5}$	$1.5 \cdot 10^{-10}$	0.05

tralino, in case it is the lightest supersymmetric particle (LSP) and when R-parity is conserved, leads to residual annihilation during BBN it is of interest to explore this case. In Fig. 3 I show the nucleosynthetic signatures of annihilating neutralinos in D/H, ^{7}Li/H, and ^{6}Li/^{7}Li as a function of $\Omega_b h^2$. Here the light solid, long-dashed, and dotted lines correspond to residual hadronic annihilation from light 5 and 10 GeV neutralinos with varying s-wave annihilation cross sections $\langle \sigma v \rangle = 3$ and 5×10^{-26}cm^3/s. These values of $\langle \sigma v \rangle$ correspond approximately to those required for a thermal freeze-out of neutralino annihilations before (and after) the QCD transition to yield $\Omega_\chi h^2 \approx 0.1126$. Though such models formally violate the LEP lower bound on the mass of the lightest neutralino $m_\chi \gtrsim 50\,$GeV, this latter bound implicitly assumes gaugino mass unification at the GUT scale. When this assumption is dropped, $m_\chi \approx 5\,$GeV neutralinos remain a viable dark matter candidate [45]. It is seen, that with respect to SBBN, the ^{7}Li overproduction problem is hardly alleviated, while such models produce ^{6}Li in excess of that observed in Pop II stars. ^{6}Li overproduction results particularly for lower m_χ and larger $\langle \sigma v \rangle$, as here residual annihilation is at it's strongest. To obtain the desired destruction of ^{7}Li models would lead to a factor $10 - 20$ overproduction of ^{6}Li. Models with p-wave annihilation $\langle \sigma v \rangle \sim T/m_\chi$ fare somewhat better, but at the expense of introducing exessively large annihilation rates. In any case, residual annihilation of dark matter particles seems not to be capable of explaining at the same time, the apparent SBBN ^{7}Li overproduction problem and the ^{6}Li abundance in low-metallicity stars.

I have so far implicitly assumed that ratios of D/H $\sim 3 - 4 \times 10^{-5}$ are observationally allowed. This may seem somewhat at odds with the observational determination of D/H= $2.78^{+0.44}_{-0.38} \times 10^{-5}$ [3]. In this context, it should be noted (as Ref. [3] did), that the formal errors given above may represent an underestimate of the true error (due to further unknown systematics). As a spurious trend of D/H with total hydrogen column density of the Lyman-α absorbers exists, with lower column density systems giving higher inferred D/H (such as Q1009+2956 with $4.0 \pm 0.65 \times 10^{-5}$ [46] or PKS 1937-
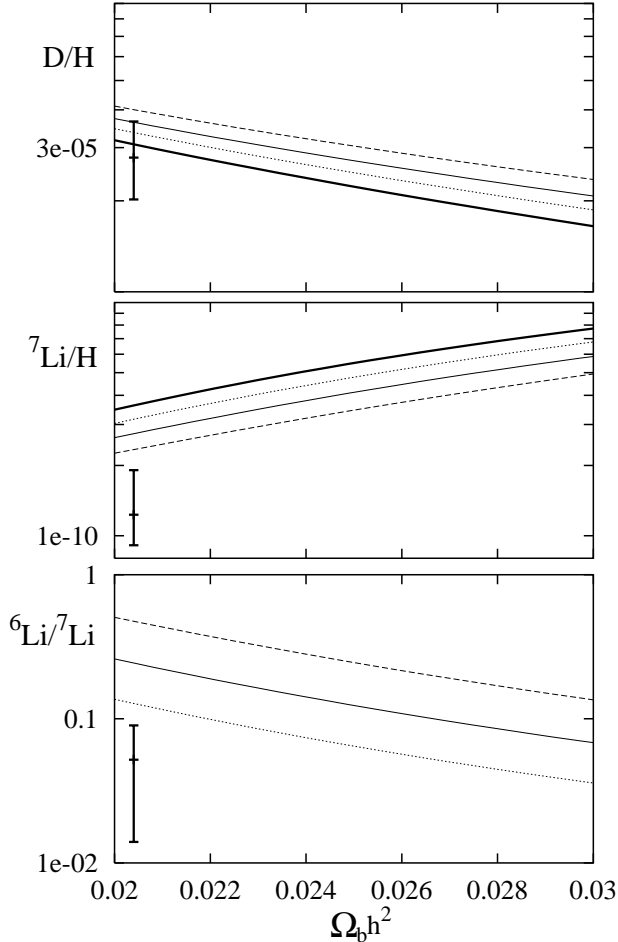
FIG. 3: Abundance yields of D/H, ^{7}Li/H, and ^{7}Li/^{6}Li in the presence of residual neutralino annihilation for a neutralino fractional contribution to the critical density of $\Omega_\chi h^2 = 0.1126$. Three models are shown: $m_\chi = 5\,\mathrm{GeV}$ and $\langle \sigma v \rangle = 3 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$ (light solid), $m_\chi = 5\,\mathrm{GeV}$ and $\langle \sigma v \rangle = 5 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$ (dashed), and $m_\chi = 10\,\mathrm{GeV}$ and $\langle \sigma v \rangle = 3 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$ (dotted). For comparison, the SBBN yields are shown by the heavy solid lines. Note the absence of appreciable ^{6}Li production in SBBN. Observational data on the D/H, ^{7}Li/H, and ^{6}Li/^{7}Li ratios indicated in the figure are as in Fig.2.

1009 with $3.25 \pm 0.3 \times 10^{-5}$ [47]), I regard primordial values of D/H $\sim 3 - 4 \times 10^{-5}$ as viable. Similarly, a baryonic density parameter of $\Omega_b h^2 = 0.026$ may seem compatible with the determination of $\Omega_b h^2$ when WMAP data is only considered, but at odds with the estimate of the combined data of WMAP and large-scale structure surveys (as well as Lyman-α forest surveys) which yields 0.0226 ± 0.0008. Nevertheless, since such analysis invokes assumptions of the underlying cosmological model, formal error bars should be taken with a grain of salt. Evidently, scenarios which are accompanied by

additional late-time photodisintegration of D (and ^{6}Li) may operate at lower $\Omega_b h^2$.

It is interesting to speculate on which relic, in fact, could cause the depletion of ^{7}Li and concommitant production of ^{6}Li. Though residual annihilation of a dark matter particle usually predicts too large of a ^{6}Li abundance, when requiring a factor $2-3$ ^{7}Li depletion, it may still represent the main source of ^{6}Li in low-metallicity stars. Alternatively, an initially high ^{6}Li may (along with the ^{7}Li) be somewhat depleted by stellar processes to reach agreement with observations on both isotopes. Other possibilities include the evaporation of Q-balls or strange quark matter nuggets, but will not be further discussed here. In light of the widely believed existence of a supersymmetric (SUSY) extension of the standard model of particle physics, particle decay may seem particularly promising, as there exist a variety of possibilities involving the gravitino. When spontaneous SUSY breaking in a hidden sector is communicated to the visible sector via gravitational interactions, or when breaking occurs due to the super-Weyl anomaly, the gravitino is heavy $\sim 0.1 - 100\,\mathrm{TeV}$ and long-lived. Moreover, it is easily produced in the primordial plasma due to two-body scatterings at high temperture T_R with abundance $\Omega_{\tilde{G}} \sim 2 \times 10^{-4}(T_R/10^8\mathrm{GeV})(\mathrm{TeV}/m_{\tilde{G}})$ [49]. It's decay into a gauge boson B and it's superpartner $\tilde{B}$ occurs with life time $\tau_{\tilde{G}} \approx 4 \times 10^5\,\mathrm{s}\,N_c^{-1}(m_{\tilde{G}}/1\,TeV)^{-3}$, where N_c is the number of available decay channels (N_c = 1 for the $U(1)_Y$ gauge boson and $N_c = 8$ for gluons). For decay into gluons one finds $\tau_{\tilde{G}} \approx 700\,\mathrm{s}$ for a 4 TeV gravitino [48], seeming somewhat large for the simplest models of supergravity and somewhat small for models of anomaly-mediated SUSY breaking. Other scenarios may result when the gravitino itself is the LSP (lightest supersymmetric particle), such as in gauge-mediated SUSY breaking (GMSB). In this case, the particle next in the mass hierarchy (NLSP) undergoes thermal freeze-out of annihilation reactions, with typical abundances of the order $\Omega_\chi h^2 \sim 10^{-4} - 10^4$ independent of the reheat temperature. The NLSP later on decays into the gravitino LSP and it's superpartner with decay time $\tau_\chi \approx 240\,\mathrm{s}(m_{\tilde{G}}/\mathrm{GeV})^2(m_\chi/300\,\mathrm{GeV})^{-5}$, thus making decay occur naturally at the desired 10^3s for GeV gravitinos. In GMSB scenarios the NLSP is frequently the bino $\tilde{B}$, right-handed stau $\tilde{\tau}$, and in a smaller part of the parameter space the higgsino $\tilde{H}$. Typical annihilation rates for $\tilde{B}$, $\tilde{\tau}$, and $\tilde{H}$ are in the ballpark 10^{-27} for the former and $10^{-25}\mathrm{cm}^3/\mathrm{s}$ for the latter two particles, yielding thermal freeze-out Ω_χ of ~ 1 and 10^{-2}, respectively. Nevertheless, a significant spread around these reference values exists. As I have shown an $B_h \Omega_\chi h^2 \approx 2 \times 10^{-4}$ is preferable, where B_h is the hadronic branching ratio capable of producing nucleons (i.e. excluding hadronic decay only generating pions as in the case of the τ). In the case of the $\tilde{\tau}$ and the $\tilde{H}$ the typical abundance comes close to this value. The $\tilde{\tau}$, however, has only a small phase-space supressed $B_h \sim g_2^2/(32\pi^2) \sim 10^{-3}$ due to the coupling of τ to ν_τ and $W^\pm$, with the latter decay-

ing into $q\bar{q}$ in seventy per cent of all cases. Here g_2 is the $SU(2)$ gauge coupling constant. An NLSP stau may thus only work for $\Omega_{\tilde{\tau}} \sim 0.1 - 1$, demanding it to be rather heavy $m_{\tilde{\tau}} \sim 1\,\text{TeV}$. For a Higgsino one has $B_h \sim 0.1 - 1$ due to it's decay into heavy quarks or massive gauge bosons, such that a Higgsino NLSP may have the desired properties. Such scenarios may also be consistent with the gravitino being the dark matter particle and successful leptogenesis occurring at reheat temperatures $T_R \sim 10^{10}\,\text{GeV}$ [50]. Finally, a typical bino abundance seems too large since the bino B_h is usually appreciable (~ 0.1) due to decay into the Z boson. Nevertheless, in this case B_h may be phase space suppressed for $m_{\tilde{B}}$ not much larger than the Z mass. Particularly interesting in this case of $B_h \ll 1$ is also the possible later photodisintegration of D, possibly removing the requirement to operate at $\Omega_b h^2 \gtrsim 0.025$. Such decay is also associated with an, albeit small, component of gravitino hot dark matter [51]. Last but not least, the particle with the required properties may also be a super-WIMP occurring in Kaluza-Klein theories [52].

In summary, I have presented first results of a newly developed Monte Carlo code examining the nuclear cascade development and cascade nucleosynthesis resulting from the putative injection of energetic nucleons during the epoch of BBN. Such an injection may result by a variety of means, such as, the decay of gravitinos, the decay of NLSP's to gravitinos, the evaporation of Q-balls or strange quark matter nuggets, or the residual annihilation of light neutralinos, among others. This most detailed numerical tool of this sort to date, has been applied in the regime of a "comparatively" weak perturbation during BBN leaving the primordial ^4He abundance virtually unchanged when compared to SBBN. However, sources of this kind may still have dramatic effects on the synthesized D, ^7Li, and ^6Li yields. In particular, I have found that due to injection of neutrons near $\tau \approx 10^3\text{s}$ an efficient reduction of the final ^7Li yield may result. Such a factor 2-3 reduction of ^7Li is just what is needed to re-

solve the tension between the observationally inferred low $^7\text{Li/H}$ ratios in low-metallicity Pop II stars and the theoretically predicted high $^7\text{Li/H}$ ratio in SBBN. Of course, this holds true only if the ^7Li in these stars is not subject to some significant stellar depletion. In the simplest scenarios, destruction of ^7Li is found to be accompanied by some production of D, though in more complicated scenarios such additional D may later be partially photodisintegrated. If photodisintegration is absent, viable scenarios may only result for $\Omega_b h^2 \gtrsim 0.025$, such that future (and current) high precision determinations of $\Omega_b h^2$ by measurements of CMB anisotropies are important for the evaluation of these models. Injection of energetic nucleons towards the end of BBN may also result in the synthesis of the ^6Li isotope, with resultant $^6\text{Li/}^7\text{Li}$ isotope ratios comparable to those observed in low-metallicity Pop II stars. This may present a viable alternative to the problematic explanation of ^6Li abundances in Pop II stars due to traditional cosmic ray nucleosynthesis.. It is intriguing to note that BBN with a weak non-thermal hadronic source, shows good potential to resolve two current discrepancies in nuclear astrophysics. In this context, particularly promising seems the decay of NLSP's to LSP gravitinos of mass $\sim 1\text{GeV}$ with NLSP freeze-out abundance either small $\Omega_\chi \approx 2 \times 10^{-4}$ when an appreciable hadronic (nucleonic) branching ratio B_h exists, or larger when $B_h \ll 1$. I have shown that this may the case for the NLSP being either the bino, stau, or Higgsino. Another viable possibility is the decay of $\gtrsim \text{TeV}$ gravitinos of abundance $\Omega_{\tilde{G}} \approx 5 \times 10^{-4}$ produced during reheating at a reheat temperature of $T_R = 10^8\text{GeV}$. I believe that such processes deserve further consideration as, if indeed they occurred, they may provide an invaluable source of information about the evolution of the early Universe and the properties of a primordial relic.

[1] R. A. Malaney and G. J. Mathews, Phys. Rept. **229**, 145 (1993); S. Sarkar, Rept. Prog. Phys. **59**, 1493 (1996)

[2] D. N. Spergel *et al.*, Astrophys. J. Suppl. **148**, 175 (2003)

[3] D. Kirkman, D. Tytler, N. Suzuki, J. M. O'Meara and D. Lubin, arXiv:astro-ph/0302006.

[4] If not state otherwise, quoted error bars are one-sigma.

[5] For example, for the same $\Omega_b h^2$ Ref. [6] obtain 4.67×10^{-10}, to be compared to the lower 3.82×10^{-10} by Ref. [7] and 4.15×10^{-10} by Ref. [8] at even higher $\Omega_b h^2 = 0.0224$, as well as 4.9×10^{-10} by Ref. [9] at $\Omega_b h^2 = 0.023$, indicating approximate uncertainties in the predictions.

[6] S. Burles, K. M. Nollett and M. S. Turner, Astrophys. J. **552**, L1 (2001)

[7] R. H. Cyburt, B. D. Fields and K. A. Olive, astro-ph/0312629

[8] A. Coc, E. Vangioni-Flam, P. Descouvemont, A. Adahchour and C. Angulo, astro-ph/0401008

[9] A. Cuoco, F. Iocco, G. Mangano, G. Miele, O. Pisanti and P. D. Serpico, astro-ph/0307213

[10] S. G. Ryan, T. C. Beers, K. A. Olive, B. D. Fields and J. E. Norris, Astrophys. J. Lett. **530**, L57 (2000)

[11] P. Bonifacio, et al., Astron. Astrophys. **390**, 91 (2002)

[12] M. Asplund, M. Carlsson and A. V. Botnen, Astron. Astrophys. **399**, L31 (2003)

[13] M. Lemoine, D. N. Schramm, J. W. Truran and C. J. Copi, Astrophys. J. **478** 554 (1997)

[14] E. Vangioni-Flam, et al. New Astronomy **4** 245 (1999)

[15] M. Salaris and A. Weiss, Astron. Astrophys. **376**, 955 (2001)

[16] S. Theado and S. Vauclair, Astron. Astrophys. **375**, 70 (2001)

[17] M. H. Pinsonneault, G. Steigman, T. P. Walker, . K. Narayanans and V. K. Narayanan, Astrophys. J. **574**, 398 (2002)

[18] V. Luridiana, A. Peimbert, M. Peimbert and M. Cervino, Astrophys. J. **592**, 846 (2003)

[19] Y. I. Izotov and T. X. Thuan, astro-ph/0310421

[20] K. Jedamzik, G. M. Fuller and G. J. Mathews, Astrophys. J. **423**, 50 (1994)

[21] M. H. Reno and D. Seckel, Phys. Rev. D **37**, 3441 (1988)

[22] K. Kohri, Phys. Rev. D **64**, 043515 (2001)

[23] S. Dimopoulos, R. Esmailzadeh, L. J. Hall and G. D. Starkman, Astrophys. J. **330**, 545 (1988)

[24] Y. L. Levitan, I. M. Sobol, M. Y. Khlopov and V. M. Chechetkin, Sov. J. Nucl. Phys. **47**, 109 (1988); E. V. Sedelnikov, S. S. Filippov and M. Y. Khlopov, Phys. Atom. Nucl. **58**, 235 (1995).

[25] V. V. Smith, D. L. Lambert, and P. E. Nissen, Astrophys. J. **408** 262 (1993); **506** 405 (1998); L. M. Hobbs and J. A. Thorburn, Astrophys. J. **491** 772 (1997); R. Cayrel, M. Spite, F. Spite, E.Vangioni-Flam, M. Cassé, and J. Audouze, Astron. & Astrophys. **343** 923 (1999); P. E. Nissen, M. Asplund, V. Hill, and S. D'Odorico, Astr. & Astrophys. **357** L49 (2000)

[26] P. E. Nissen, D. L. Lambert, F. Primas, and V. V. Smith, Astr. & Astrophys. **348** 211 (1999)

[27] It may be that this is simply a selection effect as most of these claimed detections are only around 2σ.

[28] K. M. Nollett, M. Lemoine, and D. N. Schramm, Phys. Rev. **C56** 1144 (1997)

[29] E. Vangioni-Flam, M. Cassé, R. Cayrel, J. Audouze, M. Spite, and F. Spite, New Astron. **4** 245 (1999); B. D. Fields and K. A. Olive, New Astron. **4** 255 (1999)

[30] R. Ramaty, S. T. Scully, R. E. Lingenfelter and B. Kozlovsky, Astrophys. J. **534**, 747 (2000)

[31] A. Alibés, J. Labay, and R. Canal, Astrophys. J. **571**, 326 (2002)

[32] T. K. Suzuki and S. Inoue, Astrophys. J. **573** 168 (2002)

[33] K. Jedamzik, Phys. Rev. Lett. **84**, 3248 (2000)

[34] Such considerations are also very useful to derive constraints on late-decaying particles in the early Universe.

[35] The analysis does currently not include the effects from antinucleons. An antinucleon scatters not more than 1-2 times on nucleons before an annihilation reaction occurs. Due to the small ^{4}He/H ratio it thus has a probability of roughly 10% to annihilate on ^{4}He, thereby producing around ~ 0.3 D, ^{3}He, and ^{3}H per annihilation. One may therefore expect ~ 0.03 D, (^{3}He and ^{3}H) per injected antinucleon. This should be compared to ~ 1 D (see text further below) produced per annihilation by injected energetic nucleons, since those latter may scatter of the order 10-20 times before falling below the threshold for ^{4}He spallation.

[36] M. S. Smith, L. H. Kawano and R. A. Malaney, Astrophys. J. Suppl. **85**, 219 (1993)

[37] C. Angulo, M. Arnould, M. Rayet, et al., Nucle Phys. **A656** 3 (1999)

[38] T. Sjöstrand, P. Edén, C. Friberg, L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin, Computer Physics Commun. **135** 238 (2001); www.thep.lu.se/ torbjorn/Pythia.html

[39] For higher particle masses $m \gtrsim 1$ TeV, the ratio of secondary to primary neutrons is more of the order of ~ 10.

[40] Note here, that predictions become less accurate for higher mass particles due to poor reaction rate data at high energies. Whereas the typical energy of a nucleon generated during the decay of a $m_\chi = 200$ GeV particle is 8 GeV , it is 55 GeV for a $m_\chi = 4$ TeV particle.

[41] The decay may still be envisioned as baryon-number non-violating, as it may be associated with the injection of one $\bar{n}\bar{p}$ pair. These latter particles predominantly annihilate on protons, thus effectively yielding the injection of one energetic np pair, and the annihilation of two thermal protons. In any case, due to the weakness of the source, the removal, or non-removal, of thermal protons has a negligible effect on the final result. As argued above [35], cascade produced D due to antinucleon-annihilation on ^{4}He is a subdominant $\sim 10\%$ effect, which nevertheless, becomes stronger for lower energy primary nucleons.

[42] K. Enqvist and A. Mazumdar, Phys. Rept. **380**, 99 (2003)

[43] E. Witten, Phys. Rev. D **30**, 272 (1984)

[44] J. L. Feng, A. Rajaraman and F. Takayama, Phys. Rev. D **68**, 063504 (2003)

[45] A. Bottino, N. Fornengo and S. Scopel, Phys. Rev. D **67**, 063519 (2003)

[46] S. Burles and D. Tytler, arXiv:astro-ph/9712109.

[47] S. Burles and D. Tytler, Astrophys. J. **499**, 699 (1998)

[48] Even when the decay channel into gluons, for example, due to kinematic reasons is disallowed, decay into the $U(1)_Y$ B-gauge boson may induce the injection of nucleons, since the B is a mixture between the photon and the Z, with the latter having an appreciable branching ratio into quarks. Nevertheless, in this case a gravitino mass of the order of 8 TeV is required.

[49] T. Moroi, H. Murayama and M. Yamaguchi, Phys. Lett. B **303**, 289 (1993); M. Bolz, A. Brandenburg and W. Buchmuller, Nucl. Phys. B **606**, 518 (2001)

[50] M. Bolz, W. Buchmuller and M. Plumacher, Phys. Lett. B **443**, 209 (1998)

[51] K. Jedamzik, M. Lemoine and G. Moultaka, in preparation

[52] J. L. Feng, A. Rajaraman and F. Takayama, Phys. Rev. Lett. **91**, 011302 (2003)